Floating Gate Dosimetry Based on Measurement of Incremental Charge Injection

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Abstract

A novel method of using a UVPROM as both a dosimeter and a micro-dosimeter has been developed. Like previous floating gate dosimeter methods, this method uses charge removed from the floating gate as the metric for measuring dose. Unlike previous methods, this method does not use the amount of UV to attain equivalent erasure to measure the dose and also does not require UV as a calibration tool. This method uses amount of charge injected into a cell as the method of measuring dose. This allows for dose measurements without UV as well a dose measurement of each cell.

I. INTRODUCTION.

As space missions using COTS parts become more integrated, the use of low power, multistep floating gate non-volatile memories (NVMs) will definitely increase. The use of this technology for upcoming long-term missions like X2000 or Europa requires the erasure of the floating gate to be well understood. The further proliferation of small volume and micro-dose effects will continue to be a collective issue, especially pertinent to stuck bits, hard Single Event Functional Interrupt (SEFI) and Single Event Gate Rupture (SEGR) of ultra-thin low voltage gates. This research uses a FAMOS based UVPROM in an atypical way to measure the dose deposited to a single UVPROM cell.

The erasure mechanism of the FAMOS cell is the injection of holes into the oxide around the floating gate. Some of the injected electrons will reach the floating gate and remove charge by combining with the electrons on the floating gate. Ionizing radiation generates electron-hole pairs in the oxide, and the hole that survives the recombination will cause the removal of the charge from the floating gate, after the hole migrates to the floating gate [1,2]. This change in charge on the floating gate can be measured and several different approaches have been employed to use this device as a dosimeter [3-7]. In the UVPROMs used in this study, the readout of a device used as a memory results in the programmed state reading out as logical low (or 0) and the unprogrammed state as logical high (or 1). Previous research using this device has employed charge removal off the floating gate to measure change in the time to erase with UV as reported on the pins of the device. This research seeks to increase the accuracy and precision of these measurements orders of magnitude by eliminating UV as the calibration standard and replacing it with controlled charge injection. These advances in floating gate dosimetry methods will allow for precise and very compact dosimeter suitable for personnel or long term remote applications.

II. THEORY AND BACKGROUND

The theory of UVPROM based floating gate dosimetry has been well document in previous studies [3-7]. For this study, the fundamental idea is the same. The charge removed from the floating gate by radiation can be measured since the charge is a monotonically decreasing amount with dose. Figure 1 illustrates a band diagram of an empty, or unprogrammed, floating gate FET. The dark line immediately above the Fermi level represents the energy due to trapped electrons. As electrons are added to the floating gate, the energy level will rise and the channel will invert, transisting from conducting to non-conducting. Figure 2 shows a typical circuit for determining when a FAMOS FET will transist past a certain reference voltage. A circuit of this function is reflected in Figure 2 is assumed to be representative of the device under test in this study.

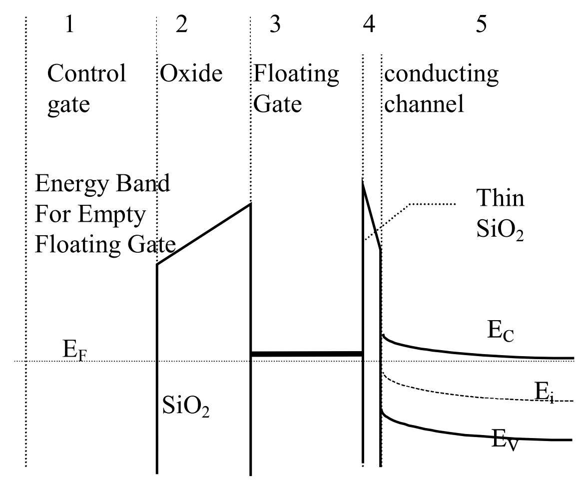

Figure 1: Band diagram for a FAMOS FET.

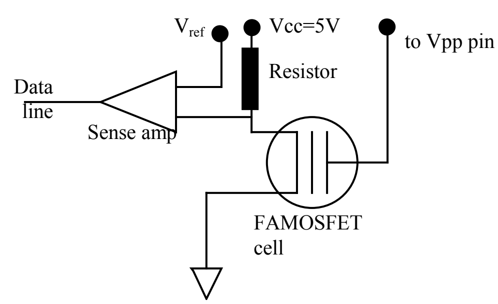

Figure 2: A FAMOS transistor and readout scheme. The floating gate stores charge so the device may power down and still retain data. Ionizing radiation removes charge from the floating gate.

The FAMOS transistor can be used as a dosimeter by taking advantage of its properties as a static memory cell. The transistor has two gates: a control gate at bias Vpp and a floating gate which is insulated from the rest of the circuit. The floating gate controls whether or not the channel of the FAMOS FET is conducting. Operation with only the fully erased or fully charged gate is the commercial mode of use. The application of the floating gate as a dosimeter is based on the partial removal of charge and the ability to measure the change. Any radiation that can deposit enough energy to remove electrons from the floating gate directly or create electron hole-pairs in silicon or the oxide may be measured [8-10].

This study investigates the use of short duration programming pulses on the device as the metric of measuring dose. Sufficiently small programming pulses should be able incrementally load the floating gate with electrons. Pulse length can range from nanoseconds to milliseconds and the both Vpp and Vcc can be varied to minimize noise or increase response. All other aspects of this study will parallel previous UVPROM dosimeter investigations to discern the change in accuracy and precision of the method of using change in erasure time with UV as the metric of dose measurement.

The need for increased autonomy and duty cycle of floating gate dosimeters necessarily required an alternative to UV being used as a metric for measuring dose. The reproduction of highly precise UV is most difficult. Mercury vapor lamps are the only reasonable source of UV for the dosimeter application of the UVPROM. These lamps are mainly used in germicidal and total erasure of UVPROMs, and are not manufactured to produce UV intensity with any precision. The lamps require a warm-up time and have a varying intensity over their lifetime. Great care must be taken, therefore, to enforce constant UV intensity in a laboratory setting. In previous studies, the UV intensity was tightly controlled[4-7].

The device also exhibits sensitivity to the manner in which UV is used to erase or calibrate the device. Figure 3 shows the importance of keeping a constant intensity. The figure depicts the time to totally erase a device as a function of UV intensity for readout at Vpp equal to 8V for the lower graph and Vpp equal to 10V on the upper graph. Since the relation of the power law is not equal to one, erasure time is not an inverse function of dose rate, and no simple correlation for a deviation in dose rate may be assumed. Figure 4 illustrates the dithering action of a single bit does when erased in various segments, or bursts, of UV. To avoid readout during UV exposure, the device is read, the device is read, which occurs in less then a second, while the UV is blocked and UV is then applied in various segments. The figure relays how long bits to completely report as erased after the first report or erasure, i.e. the amount of UV required for each bit to report a one permanently after it has reported a one. Figure 4 shows the results of various UV segment lengths and the fraction of the UV used for readout make an obvious difference. The effect of differing UV segments is also shown in Figure 5. The figure indicates the time required for the device to erase while being erased with various segments of UV with a half second readout time between the UV exposures. The relationship between longer UV segments and longer erasure time is clearly evident.

The obvious influence of intensity on both the UV generation and the device makes using UV as the metric of dose measurement hyper-dependent on the UV generation and delivery system. This dependence on UV effectively prohibits the use of multiple UV generation and delivery systems as the dose rate variable will most likely be untenable. This study seeks to eliminate UV as the metric of dose measurement and thus allow for more flexibility and precision in determining dose and micro-dose measurements.

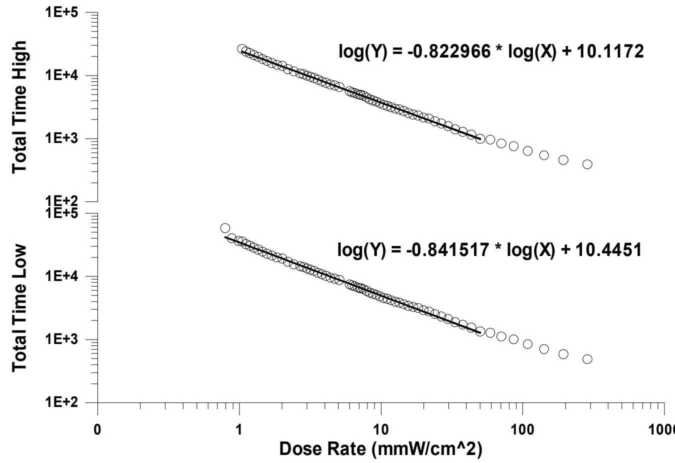

Figure 3. The dependence of UV intensity on the time to erase a UVPROM. The relation is a power law with an exponent no equal to one. This implies that the control on the UV source one must have must be precise.

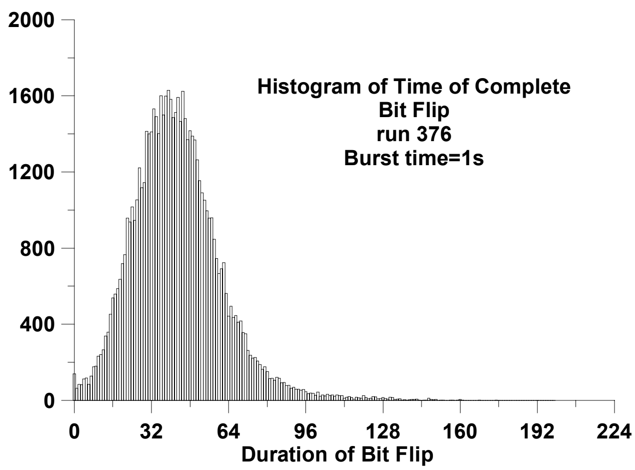

Figure 4: This histogram shows that most of the bits flip back and forth during readout. This is predominately due to the inability of UV to reach the cell with injected hole consistently.

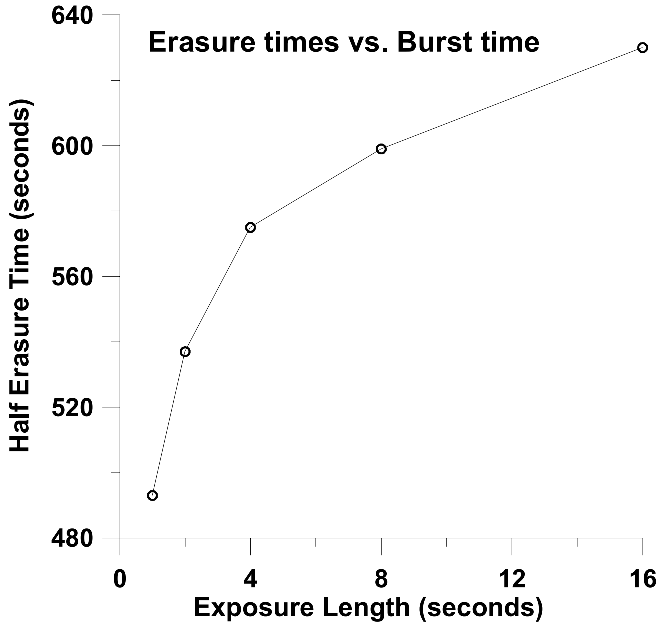

Figure 5: Time-to-erase a device as a function of UV interval length. The need to keep UV tightly controlled to make a dose measurement makes electrically priming of the FAMOS cell to the level to measure UV the next required step.

III. Setup and Procedure

The device used in this study is the AM27C64 CMOS FAMOS FET UVPROM in an 8192x8 bit format. The device operation was controlled by a PC through an interface card connected directly to the DUT. This configuration allowed the best response from the DUT. Noise reduction options were investigated including pull-down and pull-up resistors on all the data pins, decoupling capacitors on the power and data pins. Power was supplied by using a HP6629A programmable power supply. No modification or direct readout from the die was investigated since this study seeks comparison with the previous UVPROM study that also used only the readout from the pins of the DUT.

A. Use as dosimeter

To use this device as a passive dosimeter, the device is programmed and exposed to radiation. Each cell will require programming to replace the charge lost from the floating gate due to radiation. The amount of programming should correspond to dose. In practice, the device programmed with short duration pulses and a characteristic curve is developed. The period of programming time or the number of programming pulses for recovery of the programmed state can be measured from this curve. A FAMOS cell programs very quickly due to the high voltage (~12V) on the control gate. For the DUT used in this study, programming time at manufacturer specified is on the order of nanoseconds. Supply programming pulses as short as these were considered prohibitive due to noise in the lines and difficulty reproducing exact pulse on this time scale. To allow for longer pulses, the voltage on the control gate was lowered to allow for microsecond resolution of the programmed pulses required to program the device, or each cell. Figure 6 shows a family of characteristic curves from conditioning a DUT for exposure. Each curve indicates the number of programmed bits as a function of the programming time for microsecond pulses. Each curve had a different Vpp voltage applied during readout. A curve is chosen as the readout voltage and then programmed and irradiated. The resulting change in the time to program will correspond to dose.

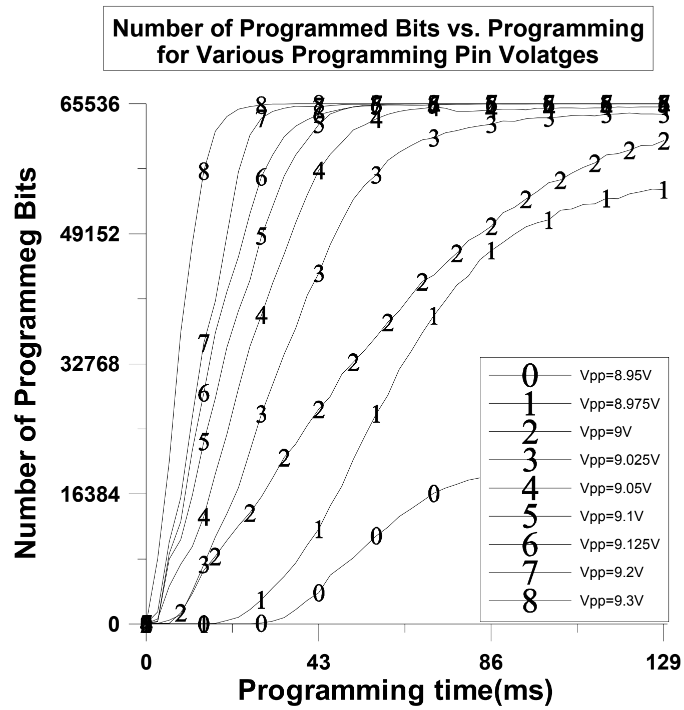

Figure 6: Typical device response to short duration programming pulses for various Vpp voltages. Increasing the voltage and using sub-microsecond pulse is prohibitive due to noise in the device.

B. Use as micro-dosimeter

Use of the UVPROM as a micro-dosimeter is conceptually the same as the dosimeter. The difference lies with addressing and programming a single bit and measuring the number of pulses that bit required to change from reporting unprogrammed to programmed, in the micro-dose case. In this manner, each cell can function as a dosimeter and report local energy deposition from rare, energetic events.

Since each cell can be electrically isolated, the number of programming pulses, or programming time, can be measured and recorded. Also, each cell can be measured for micro-dose without affecting any other cell, something that cannot be done using UV. The result of preparing one bit of a device is shown in Figure 7. Here, a bit that required 50 programming pulses to program is shown. The response of the bit shown in Figure 7 is very low noise. Some bits exhibit more instability so are therefore less precise. In practice, only bits that exhibit a clean response like the one shown in Figure 7 are used for the micro-dose measurements. Ion LET is expected to have a large effect of the response as extrapolated from previous studies [11-12]. Oxide effects are also expected to affect response [13-14].

If one measures the programming time for the same DUT for two identical runs and plots a histogram of the result, Figure 9 is that result. Figure 9 shows how identical the programming time is under the least noise conditions. Figure 9 implies that most cells program with the same number of programming time less than 5% of the time. Figure 9 was done under the least noise conditions and represents the best response of the DUT. The data was taken on a virgin DUT in tightly controlled parameters to minimize noise with Vpp of 9.1V. Increasing Vpp to increase the number of programming pulses required for programming each bit introduces flicker noise in the readings and lowers precision. Lowering Vpp shortens the programming time so that that electronics to readout and supply the programming pulses are no longer as precise. Figure 9 depicts the optimum conditions for readout and indicates the limit of the dosimeter and reliable readout is five to eight percent.

Since some of the bits of the DUT have more desirable properties for micro-dose measurement than others, a selection protocol was employed. Figure 8 shows distribution of first reports of programming of a bit for various bit programming. These plots are identical to Figure 6 except bit flips at each programming level are plotted, instead of the total number of programmed cells, as shown in Figure 6. For most micro-dose measurements, a plot like the bottom one is selected, which corresponds to a voltage selection, and bits with programming times from 20 to 40 are chosen. Bits with lesser programming times lack precision and those requiring more than that are too unstable. In practice, this procedure allows about 2 percent of the bits selected for micro-dose measurement, or about 1000 bits.

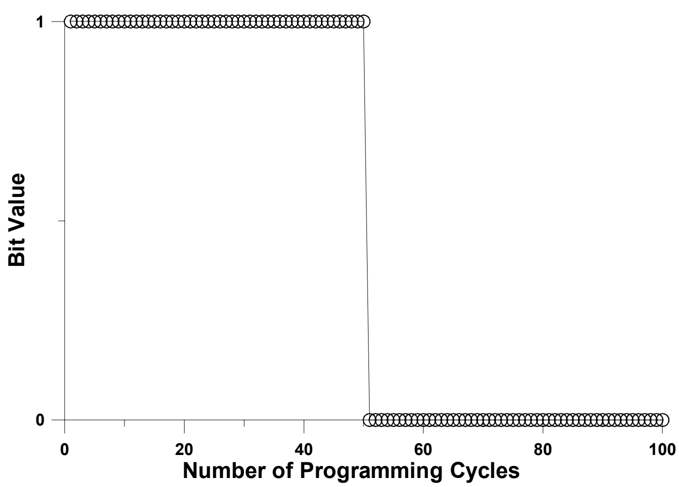

Figure 7. Programming profile of a single good bit. This bit is selected a micro-dosimeter because of the singular transition from programmed state. Vpp was 9.15V.

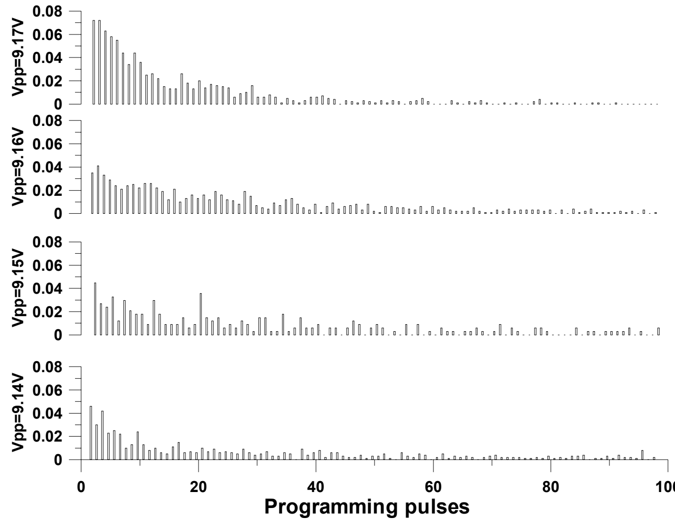

Figure 8. Distribution of programming times for four different Vpp. A distribution like this is used to find bits with acceptable noise characteristics. The selected range is 20 to 40 pulses, which select about 2 percent or 1000 of the bits for use as micro-dosimeters.

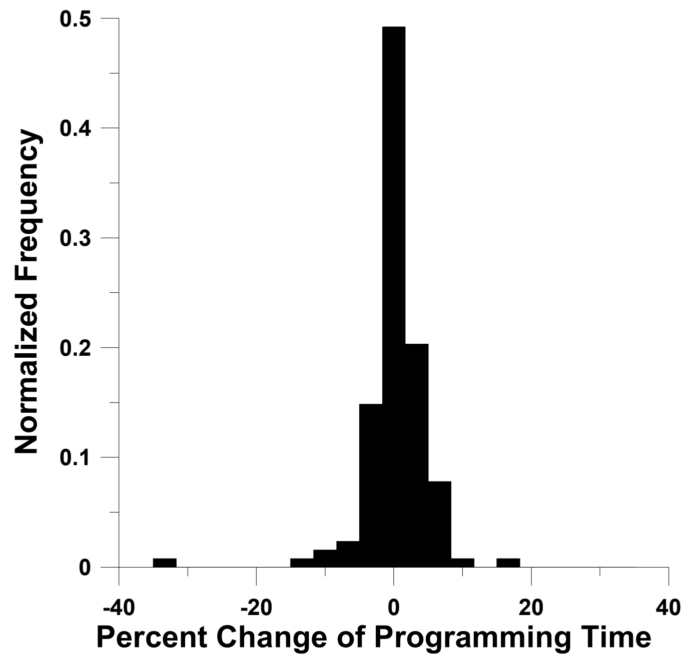

Figure 9. Best repeatability of bit to identical programming runs on the same device. The total programming time was 30 pulses, or 85.5 microsecond with Vpp=9.1V.

IV. Results

A. Dosimeter Results

Since UV light removes electrons from the floating gate, being able to measure the DUT response to UV is an important benchmark. Figure 10 shows the response of DUT used to measure UV. A completely erased curve as well a several levels of exposure to UV are included. These are typical curves, and the non-smooth levels are typical of DUT noise. Figure 11 shows the amount of programming time required to return the device to a programmed state. The relation is linear, as expected. The error bars reflect root-N deviation due to the low amount of readings the systems can report on low UV exposures. Figure 10 and Figure 11 illustrate the method of using the device as a general dosimeter.

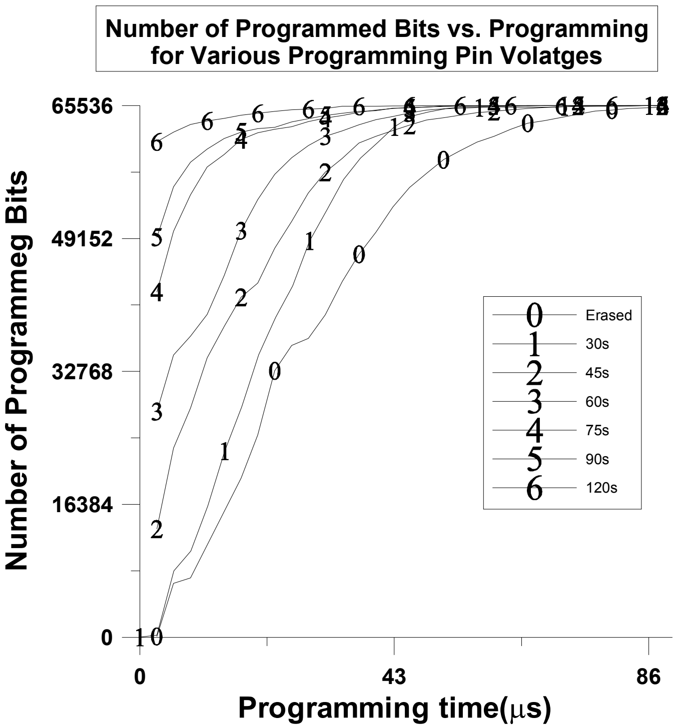

Figure 10. A total dose measurement run using UV as the radiation. This is a typical curve that shows the DUTs sensitivity to noise. Averaging compensates for the noise issues.

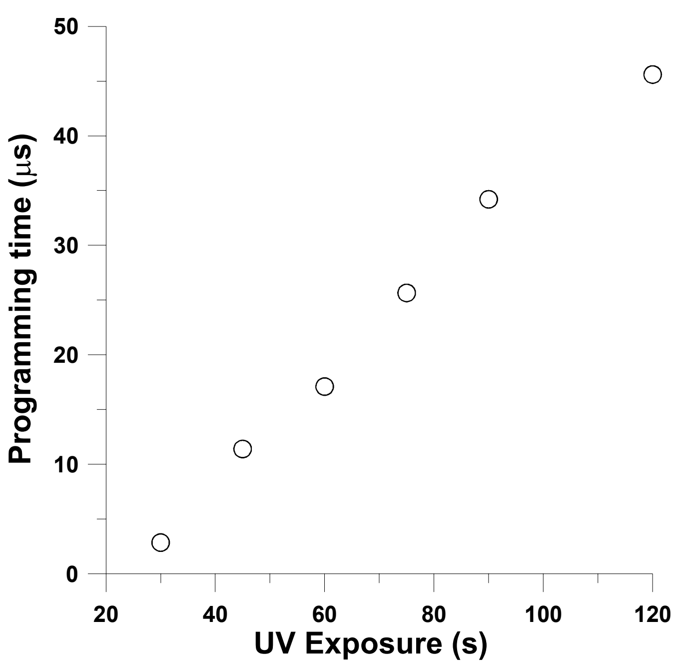

Figure 11. A total dose measurement run using UV as the radiation. This relationship was expected to be linear and is seen to be. Since the UV does not damage the device or limit endurance lifetime, this relationship reveals the upper bound of the system's precision.

Measurement of gamma from the JPL Cobalt-60 source at 50 krad(Si)/s is shown in Figure 12. Results from two DUTs are shown. The response is non-linear and has a power law response. The exponent of the power law is approximately 0.8. Gamma was expected to exhibit a similar response to measurements done in previous studies with this device. [5].

An important note concerning irradiation should be illustrated here. The response of the FAMOS cells to short pulse programming changes for an irradiated device. The voltage on the Vpp pin should be increased after irradiation. A Vpp of 9.2V to 9.5V is used for irradiated devices. This change in Vpp is due to charge building up in the channel oxide due to irradiation and has not been seen to anneal. The response of the dosimeter remains intact.

Figure 13 shows the response of two DUTs to different ions at BNL. Nickel, 400 MeV, and Chlorine, 210 MeV, were irradiated upon the dosimeters. Both responses appear to be power laws with exponents of approximately 0.6 and 0.4 respectively. This agrees well with previous studies and shows that this method can function as a dosimeter.

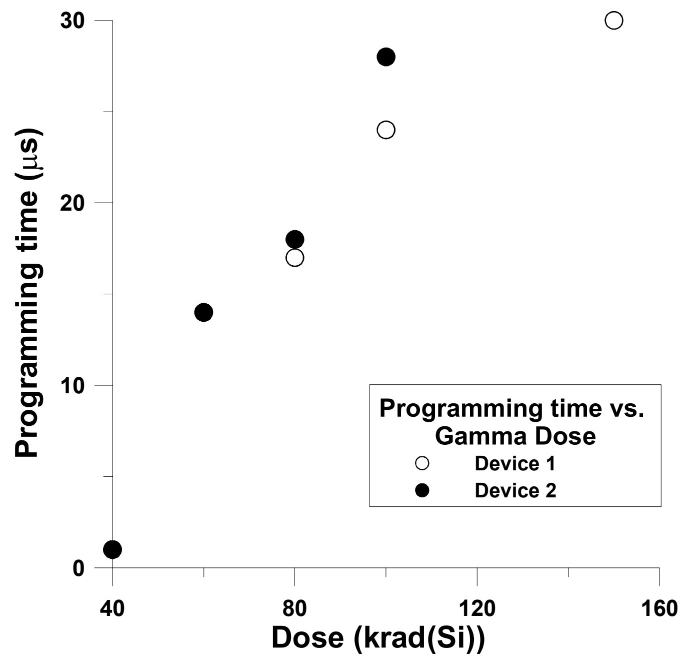

Figure 12: Total dose repsonse of two different devices of two different ion at BNL. The relationship is a power law and aggrees with earlier studies.

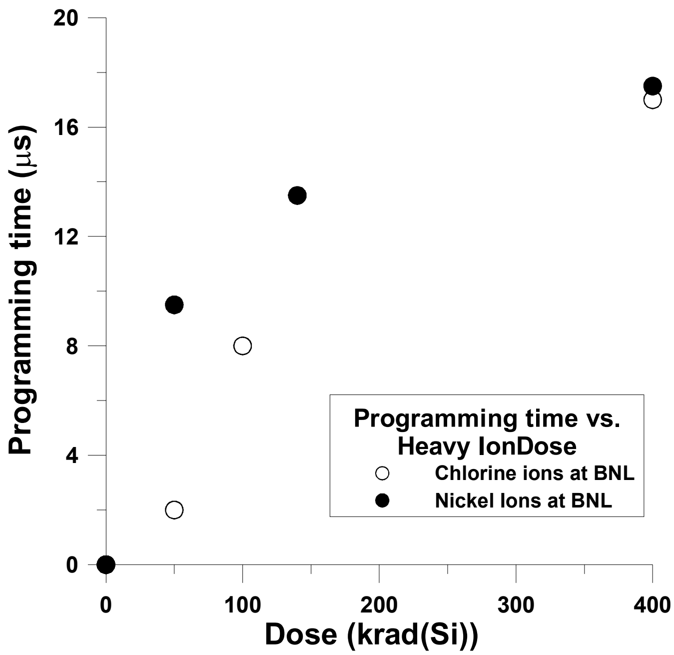

Figure 13. Total dose repsonse of two different devices of two different ion at BNL. The relationship is a power law and agrees with response indicated in earlier studies[4-7].

B. Micro-dose results.

Micro-dose results are generally defined as the response of individual cells to radiation. To determine that these devices function as micro-dosimeters, selected bits must be capable of detecting and measuring irradiation on a small scale. To observe this, six identically prepared DUT were exposed to ions of various LET. As outlined above, 1000 bits were selected. The fluence was chosen to be 3.3e7 cm^2. This fluence was assumed to hit each the area of each floating gate once on average. The irradiation was done at TAM using the Krypton and Argon 25 MeV/n beams. LET was adjusted using degraders. The result of reading out the devices for number of flips is shown in Figure 14. The figure plots the cross section per bit for reporting erasure. The point at the 30 MeV-cm^2/mg value is uncharacteristically high and is suspect; it is plotted here for completeness. The relation is monotonically increasing function and is linear if the 30 LET point is omitted. The noise in the graph is in part due to part-to-part variation. The spread in the data has been seen before [5].

Each bit that reports an erasure requires a certain amount of programming time to return it to the programmed state. Figure 15 shows the normalized mean programming time required to return the erased bits to the zero state. The normalization is the quotient of the average number of pulses required to program after irradiation to the mean amount need to prepare the same bits. The relation is not linear and is fitted to a logarithmic function. This agrees with previous results in the response of the device to differing LETs[4-7]. Oxide effects are assumed to play a role here [15].

Analysis from earlier studies using UV as a metric to determine the amount of effective erasure for greatly affected bits is shown in Figure 16. The relation is linear within error. The linearity of the relation in both cases indicates that the FAMOS cells erase with equal probability for any LET. This indicates that no correlation for LET is required when calculating dose to very small scale structures. Although previous studies have found a strong dependence on LET for overall DUT response, rare event erasures seem to follow a linear trend when UV is used as the metric. The conflicts with the implication derived from Figure 14 and Figure 15. And this is the only response were the two methods conflict.

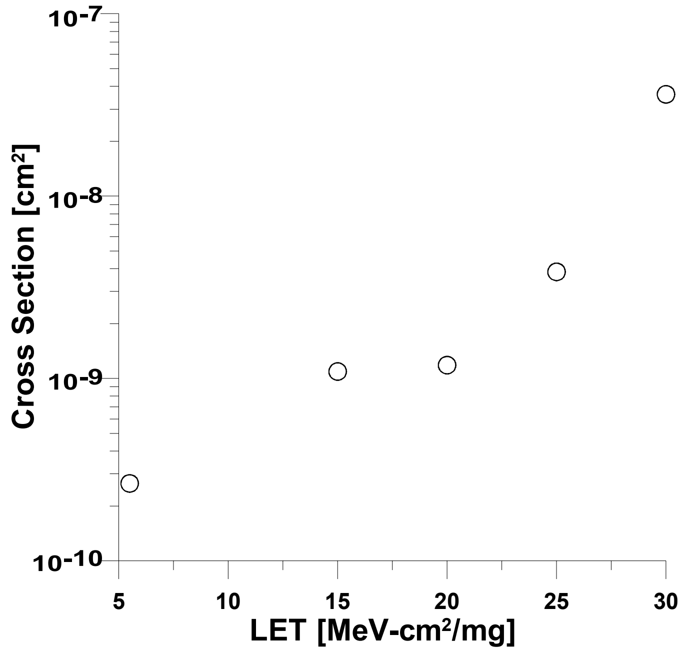

Figure 14. Bit cross section for various LETs. The ordinate values are the number of reported bit erasures divided by the number of selected bits, 1000 in this experiment, and fluence on the part, 3.3e7 cm^2, to hit each floating gate once.

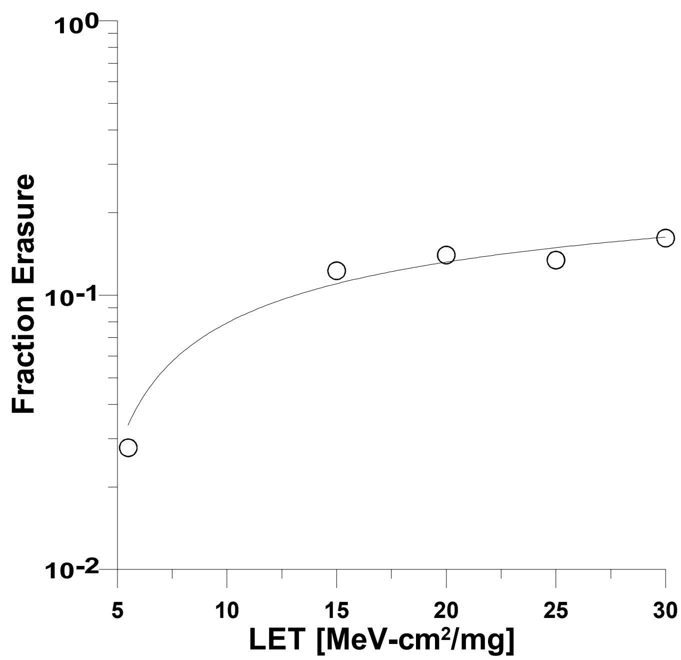

Figure 15. Normalized mean programming time for various LETs. Each cell that reported erasure requires a number of programming pulse to return it to the programmed state. The ordinate value to the average programming time require to return the bit to the programmed

states divided by the number of programming pulse require to prepare the device.

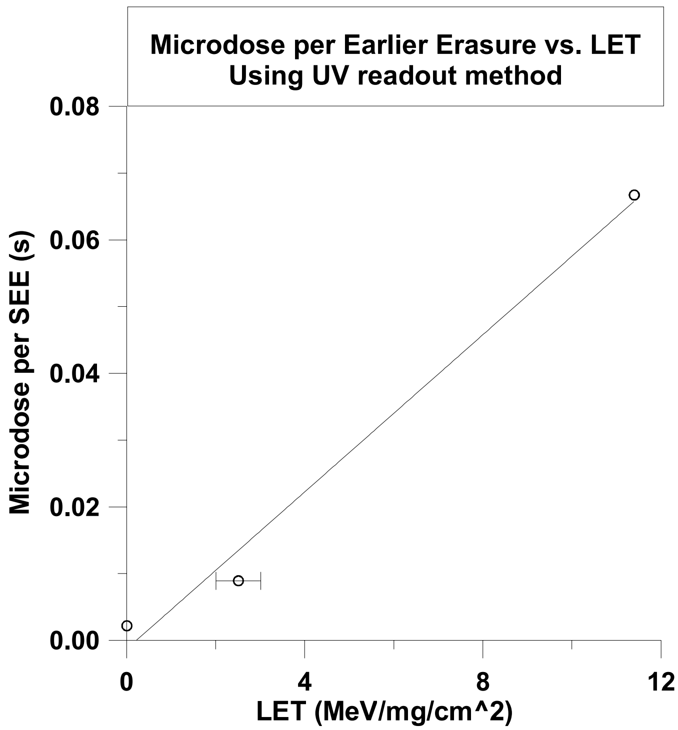

Figure 16. Amount of effect on outlying bits for the UV readout method outlined in reference 5 and similar to the results of reference 16. These are driven out from the distribution apparently by large, rare events.

V. CONCLUSION

A new dosimetry approach using FAMOS FETs has been developed. Ionizing radiation neutralizes the charge on the gloating gates, the neutralization being measurable directly from the die of the device. An estimate of the absorbed dose to a single cell can be obtained using available procedures and algorithms.

ACKNOWLEDGMENTS

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REFERENCES

[1] B. Prince and G. Due-Gundersen, *Semiconductor Memories*, New York: John Wiley and Sons, 1983.

[2] E. Nicollian and J. Brews, *MOS Physics and Technology*, New York: John Wiley and Sons, 1982.

[3] Patent number 5,961,699.

[4] L. Scheick, P. McNulty, and D. Roth, "Dosimetry based on the erasure of the floating gates in the natural radiation environments in space," *IEEE Trans. Nucl. Sci*., vol. 45, no. 6, pp. 2681-2688, 1998.

[5] L. Scheick, P. McNulty, D. Roth, B. Mason, and M. Davis,, "Measurements of dose with individual FAMOS transistors," *IEEE Trans. Nucl. Sci*., vol. 44, no. 6, pp. 1751-1756 1999.

[6] P. McNulty, L. Scheick, and D. Roth, "First failure predictions for EPROMs of the type flown on the MPTB satellite," *IEEE Trans. Nucl. Sci*, Vol: 47 Issue: 6 Part: 3 , Dec. 2000 Page(s): 2237 -2243.

[7] Scheick, L.Z.; McNulty, P.J., Roth, " Senenstive volume measurement ", *IEEE Trans. Nucl. Sci*, Vol: 47 Issue: 6 Part: 3 , Dec. 2000 Page(s): 2237 -2243

[8] E. S. Yang, *Electronic Devices.* MacGraw Hill: NY 1993.

[9] W. Brown, *Nonvolatile Semiconductor Memory Technology*. IEEE Press, 1998.

[10] T. P. Ma and P.V. Dressendorfer, *Ionizing Radiation Effects in MOS Devices and Circuits*, New York: John Wiley and Sons, 1989.

[11] P. E. Dodd, O. Musseau, M. R. Shaneyfelt, F. W. Sexton, C. D'hose, G. L. Hash, M. Martinez, R. A. Loemker, J. L. Leray, and P. S. Winokur, "Impact of ion energy on single-event upset," *IEEE Trans. Nucl. Sci*., vol. 45, no. 6, pp. 2483-2491, 1998.

[12] Rosenfeld, A.B.; Bradley, P.D.; Cornelius, I.; Kaplan, G.I.; Allen, B.J.; Flanz, J.B.; Goitein, M.; Van Meerbeeck, A.; Schubert, J.; Bailey, J.; Takada, Y.; Maruhashi, A.; Hayakawa, Y "A new silicon detector for microdosimetry applications in proton therapy." Nuclear Science, IEEE Transactions on , Volume: 47 Issue: 4 Part: 1 , Aug. 2000 Page(s): 1386 -1394

[13] Saigne, F.; Dusseau, L.; Fesquet, J.; Gasiot, J.; Ecoffet, R.; Schrimpf, R.D.; Galloway, K.F. "Experimental procedure to predict the competition between the degradation induced by irradiation and thermal annealing of oxide trapped charge in MOSFETs" *IEEE Trans. Nucl. Sci*, Volume: 47 Issue: 6 Part: 3 , Dec. 2000 Page(s): 2329 -2333

[14] O. Flament, J. Autran, P. Paillet, P. Roche, O, Faynot, and R. Truche, "Charge pumping analysis of radiation effects in locos parasitic transistors," *IEEE Trans. Nucl. Sci*., vol. 44, no. 6, pp. 1930-1938, 1998.

[15] B.D. White,.; Brillson, L.J.; Lee, S.C.; Fleetwood, D.M.; Schrimpf, R.D.; Pantelides, S.T.;Lee, Y.-M.; Lucovsky, G. "Low energy electron-excited nanoscale luminescence: a tool to detect trap activation by ionizing radiation" *IEEE Trans. Nucl. Sci*, Volume: 47 Issue: 6 Part: 3 , Dec. 2000 Page(s): 2276 -2280.